Direction Finding from Aerial Platforms with Amateur Radio Digital Arrays

1 Organization and Mission

California Polytechnic State University (Cal Poly), San Luis Obispo is a public university in San Luis Obispo County, adjacent to the city of San Luis Obispo. It is the oldest of three polytechnics in the California State University system.

1.1 Mission Statement

Cal Poly Corporation is a valuable strategic partner dedicated to advancing Cal Poly's mission. We provide vital university resources and services, enhancing campus life with solutions that are flexible, innovative and effective. Our revenues stay on campus to support programs and drive student success.
[from https://www.calpolycorporation.org/wp-content/uploads/2021/01/CPC_PressKit.pdf]

The mission of the Electrical Engineering Department at Cal Poly is to educate students toward excellence in the discipline of electrical engineering and to teach them to apply their knowledge in solving practical problems in a socially responsible way. We seek to prepare students for careers of service, leadership, and distinction in engineering and other related fields using a participatory, learn-by-doing, and hands-on laboratory, project, and design-centered approach.
[from https://ee.calpoly.edu/about/mission-objectives]

1.2 Amateur Radio at Cal Poly

Cal Poly also has a strong history in amateur radio. Cal Poly Amateur Radio Club (CPARC) has a long tradition of communications service on campus and in the community of San Luis Obispo. The club was founded in 1947, making the Cal Poly Amateur Radio Club the second oldest club on campus. The Cal Poly philosophy is "Learn by Doing," and involvement in the Cal Poly Amateur Radio Club embraces this philosophy to its fullest. Our club station, W6BHZ, is equipped with high frequency radio transceivers capable of worldwide communications. The station also acts as a San Luis Obispo County Emergency Communications Center, as it is fully equipped with emergency power and radio equipment to support various public safety agencies in the event of a disaster.
[from https://www.w6bhz.org/]

2 Motivation, Objectives and Significance

Direction finding and target localization have many applications in both civilian and defense sectors. A small number of high-altitude platforms such as kites or balloons, each equipped with one amateur radio, can be viewed as a distributed digital array capable of direction finding from space. Such a system has numerous applications, for example it can serve as a powerful tool in search and rescue missions and aid first responders in finding survivors. Given the ease of deployment and low-cost nature of the system, compared to drones or satellites, the system can be immediately deployed in a disaster area to locate the survivors; however, many technical challenges exist.

Signal property-based direction finding techniques determine the directions of sources arriving at an array using super resolution algorithms such as MUSIC and ESPRIT, which significantly outperform triangulation techniques. These digital techniques need to estimate the signal covariance matrix from multiple time samples, however, if the array element locations are not exactly known and the elements are not synchronized and calibrated, the signal matrix will not be accurate, and the algorithms will fail to estimate the target locations. Direction finding requires a coherent digital beamformer, however given the distributed and sparse nature of the array elements, this proves to be a major challenge. In this scenario, time, frequency, and phase synchronization between all the aerial platforms will not be accurate, and the platforms' relative locations are also subject to uncertainty which impacts calibration. Moreover, Direction of Arrival (DoA) estimation has traditionally been conducted with linear and circular arrays with element spacings in the order of half-wavelength. The proposed system is a 3D distributed array which is mathematically a far more complicated problem, and depending on the operating frequency, the arrays are potentially very sparse and will suffer from grating lobe problems. As a result, accurate DoA estimation will require understanding the impacts of these constraints and uncertainties and finding solutions to these problems.

The proposed research aims to address the major challenges in practical realization of such systems and provide open-access resources for world-wide usage. In addition, it seeks to create a long-term Senior Project program at Cal Poly, beyond the period of performance of this project, that involves students in research and education in amateur radio digital arrays for beamforming and communication. This project has three major objectives:

1) Develop DoA algorithms for 3D-distributed sparse digital arrays and investigate the robustness of these algorithms to practical constraints and uncertainties in the signal environment.
2) Create coherent 3D-distributed digital beamformers by implementing RF ranging methods to determine the positions of the array elements for calibration and implementing wireless time-phase-frequency synchronization techniques to synchronize array operations to the extent possible.
3) Integrate amateur radios into distributed aerial platforms for DoA and conduct long-term digital beamforming and communication studies and experiments with 3D-distributed digital arrays.

The project plan provides detailed information and a timeline for completing these major objectives. The funding requested is to support students and the principal investigator (PI) in conducting both theoretical and experimental aspects of the proposed project. Given the significant importance of position information for navigation, tracking, tower and antenna siting, and medical monitoring, to name a few, we expect the findings of this study to be beneficial to mankind in a very broad context.

3 Project Plan

The project aims at developing a cost-effective platform for digital beamforming with amateur radio sparse arrays from aerial platforms. The project plan described below outlines the specific steps and assessments in completing the proposed tasks along with timeline and budget required to carry out this research.

3.1 Statement of Work

The details of the three major objectives of this proposal are outlined in this section.

1) Develop DoA codes for 3D distributed sparse arrays with the ability to perform direction finding simultaneously in both azimuth and elevation directions.
2) Perform trade studies to assess the accuracy of these DoA algorithms under uncertain and unknown factors associated with synchronization and calibration.
3) Perform tests with a coherent digital beamformer (Kraken SDR) to assess the accuracy of developed direction finding in multiple experimental outdoor setups. The experimental findings here will assess our success in the initial stage of the program.

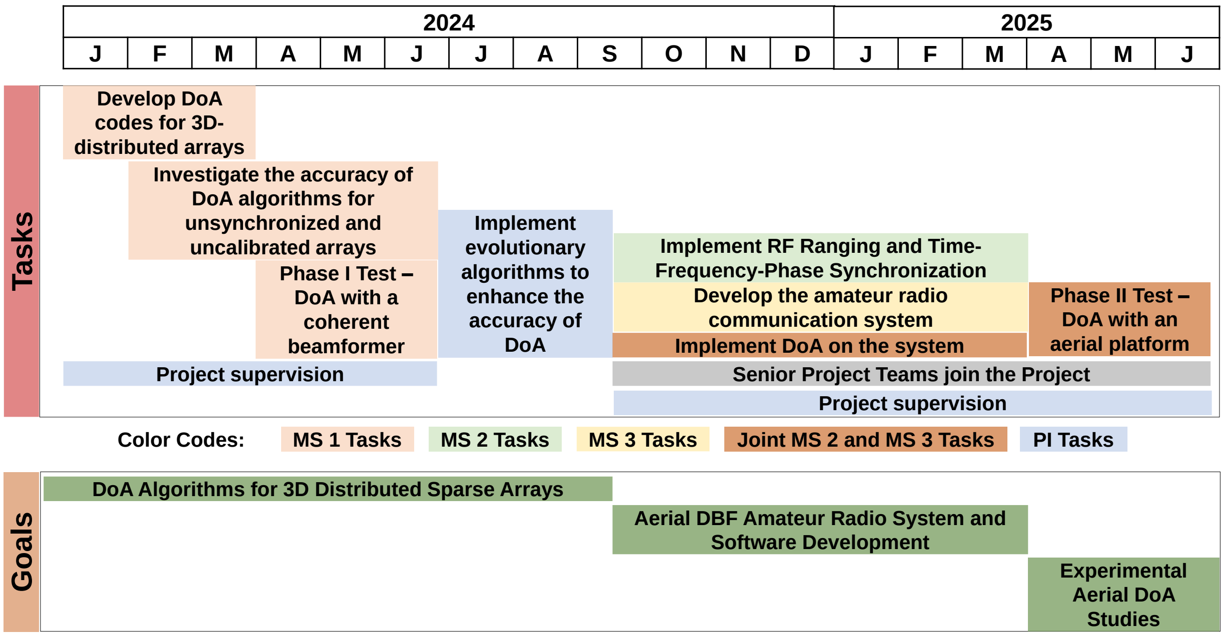
4) Develop methods that improve the performance of DoA algorithms for unsynchronized and uncalibrated arrays. We plan to use evolutionary optimization methods such as genetic algorithm which showed promise in our earlier studies.
5) Develop a systematic approach for remote ranging the location of the radios. We implement time delay (range) estimation using a dual-tone signal which maximize the estimation performance by maximizing the mean-square bandwidth of the signal spectra.
6) Develop a systematic approach for remote synchronization of the radios. We implement time synchronization by using a pulse-per-second-based time alignment and a pulsed dual-tone waveform that is matched filtered. We implement frequency and phase synchronization based on consensus averaging and Kalman filtering.
7) Use findings from studies 5 and 6 for a higher accuracy parameter estimation, based on experimental data and perform trade studies to assess the improved accuracy of distributed digital beamformer direction finding.
8) Develop mountable amateur radio systems using Raspberry Pi (please see budget) and create an experimental testbed that will be mounted on balloons. The experiment will launch the balloons to a desired height and location (tether fixed). After the initialization, the array will perform direction finding to find a target on the ground within its search range. The experimental findings here will assess our success in the final stage of the program.
9) Prepare data package, projected performance, block diagram(s), and document effort.

3.2 Deliverables

1) Open source DoA codes that can be used for direction finding by amateur radio enthusiasts and anyone who’s interested in radio science. Traditionally, digital direction finding systems use linear or circular arrays, and only perform direction finding in azimuth or elevation, but not both. The codes we provide will apply to the general case where the elements are distributed in a 3D space and will perform direction finding simultaneously in both azimuth and elevation angles. The codes will be made available as Python scripts. These codes also account for uncertainties and unknowns in the system. These include phase, amplitude, frequency, timing, and element location uncertainties of the distributed arrays, and the output of these codes will determine the accuracy of the direction finding based on these unknowns.
2) Documentation and instructional videos on remote time-phase-frequency synchronization techniques to synchronize array operations using pulse-per-second-based time alignment, pulsed dual-tone waveform that is matched filtered, consensus averaging, and Kalman filtering. In addition, we will deliver documentation and instructional videos on remote ranging of array element locations using time delay (range) estimation with dual-tone signals.
3) Documentation and presentation videos on experimental studies. Two experimental test phases are planned for the project. In the first phase the accuracy of the developed DoA algorithms will be studied using a coherent beamformer. This test will not be on an aerial platform but will be able to assess the accuracy of the direction finding codes for distributed coherent arrays with irregular shapes. The second test phase will be implemented using the amateur radio communication systems that will be developed using commercially available components in addition to some RF boards and antennas that will be fabricated in-house. This system will use remote synchronization and calibration techniques to create a coherent array to the extent possible but is expected to have some uncertainty in terms of element locations and coherency. The DoA algorithms will be assessed by using this testbed to locate the position of a target on ground from this aerial platform. Both experiments will be fully documented, and the results of these findings will be disseminated (please see section 4).

3.3 Timeline

A timetable showing the major tasks and goals of the project is given below. The tasks to be completed by the senior personnel involved in this project, 3 master-thesis degree students (MS 1-3) as well as the PI, are color coded in the table. Documentation and outreach will start from the start of the project and continue throughout the performance period. The senior project teams will join this project in Fall 2024 and further research and education in this area will be continued beyond the period of performance of the proposed project.



3.4 Budget

The total budget requested for this project is $51,945.

4 Outreach

4.1 Recruitment of Students

The PI will be supervising an EE graduate student pursuing the MS degree during the 23-24 academic year. During the Spring 2023 quarter, the student learned the basics of direction finding, and is well qualified to conduct this research. In fact, some of the theoretical aspects of this proposed work is the student's MS thesis research topic. The PI will work to recruit two graduate students for the 24-25 academic year, whose focus will be hardware development, testing, and other experimental aspects of this work. More specifically, one of the students will work on calibration and synchronization of the distributed array, while the other student will work on the amateur radio communication system and implementation of the DoA algorithms. Funding is requested to support these graduate students during the period of the proposed research.

One of the major goals of the proposed research is to create a long-term program at Cal Poly to involve students in amateur radio digital arrays. To this end, starting from the Fall 2024 quarter, we will involve senior undergraduate students as part of Cal Poly's EE Senior Project courses (EE 460, 461, and 462), to participate in this research. During the first year (24-25 academic year), these students will work with the graduate students on the experimental aspects of this project. The Senior Project program will continue beyond the 1.5-year period of performance of this proposal. Senior Project is a required course for our EE students, typically taken during their final academic year, and our department provides funding for the projects. With the strong interest in amateur radio at Cal Poly, we are confident that we will have a good number of students willing to join this project in the following years. In order to continue this program, the PI plans to create new project topics in this area every academic year and involve Cal Poly students in research and education in amateur radio digital arrays for digital beamforming and communication.

4.2 Decimation of the Findings of this Work

The principal investigator (PI) regularly attends the IEEE International Symposium on Antennas and Propagation and Radio Science Meetings (https://2023.apsursi.org/). Several amateur radio hobbyists and experts attend this symposium, and an amateur radio meeting is regularly scheduled during the symposium week. The PI will work with the students to write conference papers and present our findings at this annual international symposium in the following years. The conference papers will also be archived on IEEE Xplore. (https://ieeexplore.ieee.org/Xplore/home.jsp)

Cal Poly Amateur Radio Club (CPARC) holds regular events and meetings, and we plan to present the findings of this research at these meetings (https://www.w6bhz.org/). A recording of the presentations will also be made available on the club website.

A project webpage will be created which will contain open-access codes and documentation on how to recreate the proposed system. We will advertise this webpage on social media such as on https://www.linkedin.com/company/cparc/.

5 Alignment with ARDC's Mission

The proposed project is well aligned with ARDC’s mission, as it aims to conduct scientific research and experimentation in amateur radio digital beamforming and communication science, educate students in advanced amateur radio technologies, and further promote amateur radio science by creating open access resources and disseminating the findings of this research. The project also relies on the long-term successful impact of the Senior Project program, as well as the strong interest in amateur radio at Cal Poly, to continue research, development, education, and promotion of amateur radio digital beamforming and communication science for years beyond the period of performance of this proposal.

6 Project Team

The project PI, Payam Nayeri (KF0KDN), is an assistant professor with the EE department at Cal Poly. His research interests are in wireless communication systems with a focus on surface electromagnetics, antennas, and phased arrays, reflectarrays and array lenses, digital arrays and array processing, microwave and millimeter-wave devices, and application of artificial intelligence, machine learning, and mathematical programming techniques to these domains. He is a Senior Member of IEEE and a member of URSI (Commission B), and since 2019, has been serving as an Associate Editor for IEEE Antennas and Wireless Propagation Letters. (https://ee.calpoly.edu/faculty/pnayeri)

Cal Poly EE graduate and senior undergraduate students will be working on this project. Our EE curriculum is rich in RF and wireless courses and laboratories and combined with our ‘Learn by Doing’ mission, these students have the skillset to drive this project to success. Moreover, many of our students are members of our Amateur Radio Club (CPARC) and in general there is a very strong interest in Cal Poly for amateur radio science (https://www.w6bhz.org/).

7 Open Access

The project will use open access software for all experiments, and as such except the hardware which will be low-cost (please see project plan), anyone can use the developed codes for their own studies. The project website will contain all information about how to recreate the system, as well as downloadable codes.

8 Publications by the Author

Some of the recent relevant publications by the author in the areas of digital beamforming, radio science, and sparse arrays are given below.

[1] P. Nayeri and Randy Haupt, "Digital beamforming with unsynchronized arrays with unknown element location errors," IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, Oregon, U.S., July 2023.

[2] P. Nayeri and Randy Haupt, "Sparse hemispherical arrays with hierarchical low discrepancy sequence sampling," 17th European Conference on Antennas and Propagation (EuCAP), Florence, Italy, March 2023.

[3] Mike McNulty, Dazhen Gu, Daniel G. Kuester, and P. Nayeri, "Measurements of IP3 and P1dB for spectrum monitoring with software defined radios" European Conference on Antennas and Propagation, Madrid, Spain, March-April 2022.

[4] D. Gaydos, P. Nayeri, and R. L. Haupt, "Adaptive beamforming with software-defined-radio arrays," IEEE Access, vol. 10, pp. 11669-11678, Jan. 2022.

[5] T. Torres, P. Nayeri, Randy Haupt, and Paolo Rocca, "Sparse circular aperture arrays based on Poisson disk sampling," National Radio Science Meeting, Colorado, U.S., Jan. 2022.

[6] T. Torres, P. Nayeri, Randy Haupt, and Paolo Rocca, "Sparse cylindrical arrays with low discrepancy element spacing based on van der Corput sequence," IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, Marina Bay Sands, Singapore, Dec. 2021.

[7] [Invited Paper] T. Torres, N. Anselmi, P. Nayeri, P. Rocca, and R. L. Haupt, "Low discrepancy sparse phased array antennas," Sensors 2021, 21(23), 7816, pp. 1-20, Nov. 2021.

[8] F. Zardi, P. Nayeri, P. Rocca, and R. L. Haupt, "Artificial intelligence for adaptive and reconfigurable antenna arrays," IEEE Antennas Propag. Magazine, vol. 63, no. 3, pp. 28-38, Jun. 2021.

[9] S. Li, D. Gaydos, P. Nayeri, and M. W. Wakin, "Adaptive interference cancellation using atomic norm minimization and denoising," IEEE Antennas Propag. Letters, vol. 19, no. 12, pp. 2349–2353, Dec. 2020.

[10] D. Gaydos, P. Nayeri and R. Haupt, "Calibration and synchronization of software-defined-radio array," IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, Virtual Conference, Jul. 2020.